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ELECTROCHEMICAL BEHAVIOR OF SULFIDE AT THE SILVER ROTATING DISC--ETC(U)
MAY 81 K AOKI, K SHIMIZU, R A OSTERYOUNG N00014-79-C-0682

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TECHNICAL REPORT NO. 5

ELECTROCHEMICAL BEHAVIOR OF SULFIDE
AT THE SILVER ROTATING DISC ELECTRODE:
II. MECHANISM OF SILVER FILM FORMATION

by

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ABSTRACT

Steady state anodic voltammograms were measured at a silver rotating disc electrode in a basic sulfide solution. Analysis of the voltammograms indicates that the rate determining steps in the dissolution of silver are due to a combination of surface chemical reaction, forming silver sulfide, and the charge transfer-reaction between silver and silver ion. Kinetic parameters of each step are evaluated and an $I-E$ curve is reproduced from these parameters. The wave form is in good agreement with the voltammogram obtained experimentally.

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INTRODUCTION

Although the anodic dissolution of metals, frequently producing insoluble substances, plays an important role in the process of metal corrosion, fundamental and kinetic knowledge of such processes has been accumulated only in recent years. The mechanism of anodic dissolution contains factors making quantitative measurements difficult, e.g. influence of crystal structure, adsorption, activity change of adatoms, volume reactions, passivation due to films, surface diffusion, formation of nuclei and crystallization [1,2], and hence quantitative descriptions of such processes have been limited [3-7]. However, to a certain extent it is possible to neglect some of these effects by controlling the time scale in measurements such as in AC impedance studies [5,6], in chronopotentiometric methods [4] and in steady-state measurements at the rotating disk electrode (RDE) [3].

Much recent work in this field has been concerned with dissolution studies of zinc [8] and cadmium [9] in alkaline solutions. They show contradictory results and conditions depending on the investigators and their experimental methods. To describe anodic dissolution mechanisms comprehensively, it seems to be necessary to extensively accumulate much data with respect to many kinds of metals. The present work reports on the analysis of silver dissolution into sulfide solution as an extension of a previous study [10].

The previous experiments [10] describe the anodic dissolution of silver in basic sulfide solution at a rotating silver-disc electrode and can be summarized as follows.

(a) Silver sulfide films produced on the electrode do not block current through the electrode until the quantity of electricity passed at the electrode, Q_T exceeds 8×10^{-2} coulombs cm^{-2} . Thus, anodic currents can be regarded as steady state currents although silver sulfide is accumulated on the electrode surface as the reaction proceeds. The remarks that follow address only the case where $Q < Q_T$.

(b) The quantity of electricity passed on deposition of silver sulfide at the electrode surface, Q_a is equal to the quantity of electricity of sulfide removed in the stripping process, Q_c .

(c) From the dependence of limiting currents on the rotation rate and concentration of sulfide, it was concluded that limiting currents are controlled by diffusion of sulfide to the electrode.

(d) The potential at which anodic currents begin to flow is -0.78 V(SCE), cathodically shifted from the equilibrium potential of Ag/Ag^+ by 1.34 V.

(e) Anodic currents less than those on the limiting current plateau are kinetically controlled; and plots of $I < I_L$ vs $\omega^{1/2}$ are non-linear and are also independent of $\omega^{1/2}$ at the foot of the anodic wave.

Thus, the kinetic behavior represented by (d) and (e), supported by the rather simple results of (a), (b) and (c), encouraged us to attempt to elucidate the kinetics of the mechanism in an effort to explain the shape of the current-potential curve.

EXPERIMENTAL

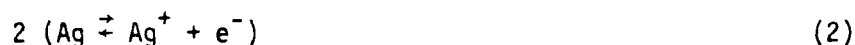
Chemicals, apparatus and experimental procedures have been described elsewhere [10]. Concentrations of sodium sulfide employed were 1.77×10^{-4} , 3.54×10^{-4} , 5.31×10^{-4} , 7.08×10^{-4} and $8.85 \times 10^{-4} \text{ mol dm}^{-3}$. Rotation rates of the silver RDE were varied from 400 rpm to 3600 rpm. The potential scan rate was 10 mV s^{-1} .

RESULTS AND DISCUSSION

An experimental voltammogram is shown in Fig. 1 as curve a. As described in prior work [10], the overall reaction which forms a silver sulfide films on the electrode is given by



This reaction can be divided intuitively into a charge transfer reaction and a chemical one as follows:



First we tentatively apply the theory for the anodic dissolution of mercury into a solution of halide ions, developed by Heyrovský and Kuta [11], to the present system. The theory assumes that anions which produce sparingly soluble salts diffuse to the electrode and equilibrate on the electrode surface with metal ions dissolving reversibly from a metal lattice. This predicts that the rate determining step is not due to reaction rates but the diffusion of anions from the bulk solution to the electrode. Then the conditions of the equilibrium in reactions (2) and (3) are given by

$$(\underline{c}_{\text{Ag}^+})_s / \underline{c}^\ominus = \exp ((F/RT)(E - E^{\circ'})) \quad (4)$$

$$(\underline{c}_{\text{Ag}^+})_s^2 (\underline{c}_{\text{S}^{2-}})_s = K_{\text{sp}} \quad (5)$$

$$(\underline{c}_{\text{HS}^-})_s / (\underline{c}_{\text{S}^{2-}})_s / (\underline{c}_{\text{H}^+})_s = K_1 \dots \quad (6)$$

where $(\underline{c}_{\text{Ag}^+})_s$, $(\underline{c}_{\text{S}^{2-}})_s$, $(\underline{c}_{\text{HS}^-})_s$, and $(\underline{c}_{\text{H}^+})_s$ are concentration of Ag^+ , S^{2-} , HS^- , and H^+ , respectively, on the electrode surface, \underline{c}^\ominus is the standard concentration (1 mol dm^{-3}) of silver ion, $E^{\circ'}$ is the formal potential of the eqn(2), K_{sp} is the solubility product of Ag_2S , and K_1

is the formation constant of the reaction, $S^{2-} + H^+ \rightleftharpoons HS^-$. The solution of the convective diffusion equation at the RDE is, in general,

$$c_s = c_0 (1 - I/I_d) \quad (7)$$

where c_s and c_0 are analytical concentrations of sulfide ($c_{S^{2-}} + c_{HS^-}$) at the electrode and in the bulk solution, respectively, and I_d and I are the diffusion-controlled current and a current depending on potential, respectively. This simple expression results from uniform accessibility of the RDE [12] and holds also for other conditions described below.

From eqns (6) and (7) one can obtain eqn. (8):

$$(c_{S^{2-}})_s \{1 + (c_{H^+})_s K_1\} = c_0 (1 - I/I_d) \quad (8)$$

Substituting eqn. (4) into eqn. (5) and eliminating $(c_{S^{2-}})_s$ from eqns. (5) and (8) yields

$$I = I_d \{1 - (K'_{sp}/c_0)(c^\ominus)^2 \exp(-2F(\underline{E} - \underline{E}^\circ)/RT)\} \quad (9)$$

where K'_{sp} is an apparent solubility product given by $K_{sp}\{1 + (c_{H^+})_s K_1\}$. The I-E curve calculated from eqn. (9) is shown as curve b in Fig. 1 for $K_{sp} = 1.6 \times 10^{-50} \text{ mol}^3 \text{ dm}^{-9}$ [13], $(c_{H^+})_s = 5 \times 10^{-4} \text{ mol dm}^{-3}$, $K_1 = 10^{14.0} \text{ mol dm}^3$ [14], and $\underline{E}^\circ = 0.555 \text{ V (SCE)}$ [15] together with curve a, which is experimental. Curve b is shifted cathodically from curve a by approximately 50 mV and rises steeply at $\underline{E} = -0.798 \text{ V(SCE)}$, ascending more steeply than curve a to reach the diffusion-controlled current plateau. Therefore, assuming the establishment of the equilibrium of reactions (2) and (3) at the electrode surface fails to reproduce the experimentally observed curve.

An alternate possibility is to introduce the kinetics of the charge-transfer process represented by the Butler equation instead of the Nernst equation. Then reaction (2) is formulated as

$$\underline{I} = 2FAk_c^\theta \{ \underline{c}^\theta \exp [(1-\alpha)F(\underline{E}-\underline{E}^{o'})/RT] - (\underline{c}_{Ag^+})_s \exp [-\alpha F(\underline{E}-\underline{E}^{o'})/RT] \} \quad (10)$$

where k_c^θ is the conditional electrode reaction-rate constant for reaction (2), α is the cathodic charge-transfer coefficient and A is the surface area of the electrode. Combining eqn. (10) to eqns. (5) and (6) yields

$$\underline{I} = 2FAk_c^\theta \{ \underline{c}^\theta \exp [(1-\alpha)F(\underline{E}-\underline{E}^{o'})/RT] - (K'_{sp}I_d/\underline{c}_o(\underline{I}_d-\underline{I}))^{1/2} \exp [-\alpha F(\underline{E}-\underline{E}^{o'})/RT] \} \quad (11)$$

which is a cubic equation with respect to \underline{I} . Values of \underline{I} computed numerically for $k_c^\theta = 2.3 \times 10^{-5} \text{ cm s}^{-1}$ and $\alpha=1$ were plotted against potentials in Fig. 1 (curve c). The values of k_c^θ and α referred here are those which will be determined in later discussion. Curve c still has a sharp rise at $\underline{E}_e = -0.798 \text{ V}$ equal to $\underline{E}^{o'} + (RT/2F)\ln(K'_{sp}/\underline{c}_o(\underline{c}^\theta)^2)$ and is very similar to curve b at the foot of the wave. Slopes of curves b and c at $\underline{E}=\underline{E}_e$ are given by $2FI_d/RT$ and $2F^2Ak_c^\theta/[RT\{(\underline{c}_o(\underline{c}^\theta)^2/K'_{sp})^{(1-\alpha)/2} + FAk_c^\theta/I_d\}]$, respectively, as a result of differentiating eqns. (9) and (11). Obviously they do not become zero for any choice of k_c^θ and α within reasonable physical meaning. Further efforts to force curve c to fit curve a for several values of k_c^θ and α , in terms of numerical calculation, failed. Therefore, it is concluded that a smooth increase in the current does not result solely from kinetics of the charge transfer but some other chemical reaction observed experimentally in a.

Since the current is proportional to a rate of a chemical reaction, the following equation can be written assuming constant concentration of sulfide at the surface, as:

$$\underline{I} = \underline{k}' (\underline{c}_{Ag^+})_s^r \quad (12)$$

In order to find the order, r , of the reaction, the logarithm of current values at the foot of the kinetically controlled waves were plotted against E (Fig. 2). This is equivalent to assuming that the charge transfer process is reversible at the foot of the wave but that the current is limited by an irreversible chemical reaction which (see (below) is a surface reaction. Values of E at the foot of the wave determine the concentration of silver ions at the electrode surface (eqn. (4)) because the charge transfer kinetics have little influence on currents at the foot of the waves, as discussed in the previous section.

Then eqn. (12) becomes

$$\ln(I/k'') = rFE/RT \quad (13)$$

Values of $r=2$ were obtained from the plots and are tabulated in Table 1 for five concentrations of sulfide solutions. Hence eqn. (12) can be rewritten, combined with reaction (3), as

$$I = FAk (c_{Ag^+})_s^2 (c_{S^{2-}})_s \quad (14)$$

Since the dimensions of k are $m \cdot s^{-1} M^{-2}$, when M is molarity, k is the rate constant of a surface reaction. The conclusion that reaction (3) is a surface reaction is further supported by the fact that silver sulfide does not escape from the electrode surface to the bulk solution during anodic polarization (10) see above.

If reaction (3) were controlled by a volume reaction in place of a surface reaction, the order r should be 1.5. This can be demonstrated as follows. The mass transport equation for the case of fast chemical reactions within the reaction layer ($0 \leq x \leq \delta$) is given by [12]

$$d^2 c_{Ag^+}/dx^2 = k''' (c_{Ag^+})^2 (c_{S^{2-}}) \quad (15)$$

At the foot of the anodic wave, the region being considered here, the

concentration of sulfide ion is constant in the vicinity of the electrode, which is expressed as $(c_s^{2-})_u$. Multiplying dc_{Ag^+}/dx on both sides and integrating the resulting equation from 0 to u yields

$$(I/F)^2 = (2/3) \underline{k}''' \underline{D}^2 (c_s^{2-})_u (c_{Ag^+})_s^3$$

which would yield a reaction order of 1.5. This is obviously inconsistent with the experimentally determined value of r . It has been reported by Bockris et al [16] that a dissolution-precipitation mechanism of calomel formation on the mercury electrode contains the rate determining step of a homogeneous chemical reaction of disproportionation of the Hg_2Cl^{+} ion.

The expression for the current complicated by the surface-chemical reaction can be derived by substituting eqns. (4) and (7) into eqn. (14) if the charge transfer step takes place reversibly. Then, it becomes

$$\ln(I/I_d - I) = \ln(\underline{FAkc}_0 (c_s^{\theta})^2 / I_d) + 2F(E - E^{\circ'})/RT \quad (16)$$

Plots of $\ln(I/I_d - I)$ against E for the foot of the wave are shown in Fig.

3. Linearity is observed at the foot of the wave and slopes of the lines are equal to $2F/RT$ and values of \underline{FAkc}_0/I_d can be evaluated from the intercept through use of $E^{\circ'} = 0.555$ V. Taking into account that I_d is given by $2 \times 6.2 \times 10^{-4} \underline{FAc}_0 D^{2/3} \nu^{-1/6} \omega^{1/2}$ [12], we notice that \underline{FAkc}_0/I_d should be proportional to $\omega^{1/2}$, where ω is the rotation rate (radian s^{-1}) of the RDE. Variation of \underline{FAkc}_0/I_d with $\omega^{1/2}$ is shown in Fig. 4. The slope of the line is $0.807 \underline{D}^{-1/2} \nu^{1/6} \underline{k}$ and hence $\underline{k} = 2.0 \times 10^{43} \text{ cm s}^{-1} \text{ M}^{-2}$. If the units of \underline{k} are converted into cm s^{-1} per atom, \underline{k} is given by $5.6 \times 10^{-5} \text{ cm s}^{-1}$ per atom, which corresponds to a conditional electrode reaction rate constant for the totally irreversible system. This linearity also demonstrates that the reaction order of S^{2-}

is unity, since if c_0 were other than first order, non-linearity would result in these plots as a result of the various concentrations of sulfide employed.

Curve d in Fig. 1 is the wave calculated from eqn. (16) with the value of k thus obtained. It overlaps the experimental curve a, at the lower part of the wave while deviating from it at the upper part.

As described previously, consideration of the kinetics of charge transfer contributes to the shape of the upper part of the wave, hence the deviation of curve d from curve a can be attributed to the kinetics of the charge transfer. In fact, the charge transfer of Ag/Ag^+ takes place quasi-reversibly [17] and hence this effect can be taken into account.

To derive the expression for a current controlled by both the surface chemical reaction (at the foot of the wave) and the charge transfer reaction (at the upper portion of the wave), we combine eqs. (7), (10) and (14) by eliminating $(c_{\text{Ag}^+})_s$ as well as $(c_{\text{S}^{2-}})_s$. By simple calculation, we have

$$\ln \frac{Hk}{c}^{\theta} = - (1-\alpha) \frac{F(E-E^{\circ'})}{RT} \quad (17)$$

where

$$H = (2FA/I) [c^{\theta} - \{(I_d/FAkc_0)(I/(I_d-I))\}^{1/2} \exp\{-F(E-E^{\circ'})/RT\}] \quad (18)$$

All of the variables involved in H are known since k has already been evaluated. Plots of $\ln (H/\text{cm}^{-1}\text{s})$ vs. E in Fig. 5 shows that $\ln (H/\text{cm}^{-1}\text{s})$ is independent of the variation of E . This requires, (Eq. 16) that $\alpha=1$, and results in a value of $k_c^{\theta}=2.3 \times 10^{-5} \text{ cm s}^{-1}$. Literature values of the kinetic parameters are $k_c^{\theta}=2.3 \times 10^{-3} \text{ cm s}^{-1}$, $\alpha=0.55$ [18] and

$k_c^\theta = 1.5 \times 10^{-4} \text{ cm s}^{-1}$ [19] where k_c^θ values have been evaluated from the exchange densities and α has been assumed to be 0.5.

The result, $\alpha=1$, implies that all the electrical part of the activation energy for the charge transfer contributes to the reduction of silver ions to silver atoms while the oxidation of silver atoms proceeds by surmounting the energy barrier which is associated only with structural chemical changes [20]. Therefore the reduction takes place as if it were a chemical reaction independent of applied potential. This is equivalent to the intuitive reaction model that sulfide ions at the electrode surface stimulate silver atoms to make the charge transfer occur and then form silver sulfide as if they plucked silver atoms from the silver lattice. In other words, the chemical affinity of sulfide and silver overcomes predominantly the strength of electric field due to the applied potential difference in the double layer.

Voltammogram calculated from eqns. (17) and (18) by means of the iterated numerical computation is drawn in Fig. 1 as curve e, and is in excellent agreement with the experimentally obtained curve a.

Since the major S-containing anion in 0.2 M NaOH solution is HS^- ($(C_{\text{HS}^-}/C_{\text{S}^{2-}}) \approx 7$) it may be necessary to take into account the dissociation rate of HS^- into H^+ and S^{2-} . S^{2-} would then correspond to the electro-active species in the sense of a preceeding chemical reaction. Then the thickness of the reaction layer is defined as $\mu = \sqrt{D/k_f[\text{H}^+]}$ [21], where k_f is the formation rate constant of HS^- from H^+ and S^{2-} . Thus the dissociation rate, v_1 , the change in the number of mole of HS^- within the reaction layer is given by $v_1 = k_d C_{\text{HS}^-} - A\mu$, where k_d is the dissociation rate constant. Since the rate of formation of weak acids are, in general,

controlled by diffusion, the rate constant may be estimated as $10^{11} \text{ s mol}^{-1} \text{ dm}^3$ [20]. Then \underline{v}_1 becomes $3 \times 10^{-5} \text{ mol s}^{-1}$ by use of formation constant of HS^- , $10^{14} \text{ mol}^{-1} \text{ dm}^3$. On the other hand, the rate of the surface reaction, \underline{v}_2 , is equal to $\underline{I}/\underline{F}$, by eqn. (14) and is less than $2 \times 10^{-8} \text{ mol s}^{-1}$. Comparison of \underline{v}_2 with \underline{v}_1 thus makes it unlikely that kinetics of dissociation of HS^- participate in the overall reaction.

CONCLUSION

Formation of silver sulfide from silver and sulfide can be separated formally into two reactions (2) and (3). We cannot differentiate if reactions (2) and (3) really take place stepwise or not. Since the kinetics equations that we know is for charge transfer reaction (2) or chemical reaction (3), combining the former with the latter allows us to discuss the overall reaction quantitatively.

If reactions (2) and (3) are in equilibrium, the current is expressed by eqn. (9) resulting in the calculated curve b of Fig. 1. The wave form controlled by the charge transfer step in the chemical equilibrium is given by curve c. Both curves are different from experimental curve a in overall morphology. It was found in Fig. 2 that the stoichiometric number of reaction (3) was 2, indicating the surface chemical reaction. The surface chemical reaction rate constant was obtained in Fig. 3. This permitted the calculation of the I-E curve of curve d, Fig. 1. These considerations, plus the consideration of the kinetics of reaction (2) results in curve e, which is consistent with the experimentally obtained curve a. It seems to us that the above procedures should play a vital role in the analysis of anodic dissolution waves for any other systems.

The significant results of examining the I-E curves are that reaction (3) occurs on the electrode surface and that the charge transfer coefficient is equal to unity. This not only accounts for features (a)-(e) of the I-E curves described in the Introduction but also provides us with a profile of the activation potential energy for reaction (1).

ACKNOWLEDGEMENT

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Table 1.

Reaction order, \underline{r} , for silver ion obtained from plots of $\ln(I/10^{-6}A)$ against \underline{E} .

$\underline{c}_0 \times 10^4 / \text{mol dm}^{-3}$	reaction order, \underline{r}
1.77	1.91
3.54	1.89
5.31	2.06
7.08	2.06
8.85	1.91
average	1.97

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FIGURE CAPTIONS

Fig. 1. Anodic voltammograms at the silver RDE. (a): experimentally obtained curve, (b): calculated from eqn. (7), (c): calculated from eqn. (9), (d): calculated from eqn. (13) and (e): calculated from eqns. (14) and (15) under the conditions of $c_0 = 5.31 \times 10^{-4} \text{ mol dm}^{-3}$, rotation speed: 1600 rpm and $I_d = 0.725 \text{ mA}$.

Fig. 2. Variations of $\ln(I/10^{-6} \text{ A})$ with E in the $5.31 \times 10^{-4} \text{ mol dm}^{-3}$ sodium-sulfide solution at rotation speeds of (Δ): 400 rpm, (\diamond): 900 rpm, (\heartsuit): 1600 rpm, (\odot): 2500 rpm and (\circ): 3600 rpm.

Fig. 3. Plots of $\ln(I/(I_d - I))$ vs. E in the $5.31 \times 10^{-4} \text{ mol dm}^{-3}$ sodium-sulfide solution at rotation speeds of (Δ): 400 rpm, (\diamond): 900 rpm, (\heartsuit): 1600 rpm, (\odot): 2500 rpm and (\circ): 3600 rpm.

Fig. 4. Dependence of kc_0FA/I_d on inverse square roots of rotation speeds in (Δ): 1.77, (\diamond): 3.54, (\heartsuit): 5.31, (\odot): 7.08 and (\circ): 8.85 $\times 10^{-4} \text{ mol dm}^{-3}$ sodium sulfide solutions.

Fig. 5. Variations of $\ln(H/\text{cm}^{-1} \text{ s})$ with E in $5.31 \times 10^{-4} \text{ mol dm}^{-3}$ sodium sulfide solution at rotation speeds of (Δ): 400 rpm, (\diamond): 900 rpm, (\heartsuit): 1600 rpm, (\odot): 2500 rpm and (\circ): 3600 rpm.

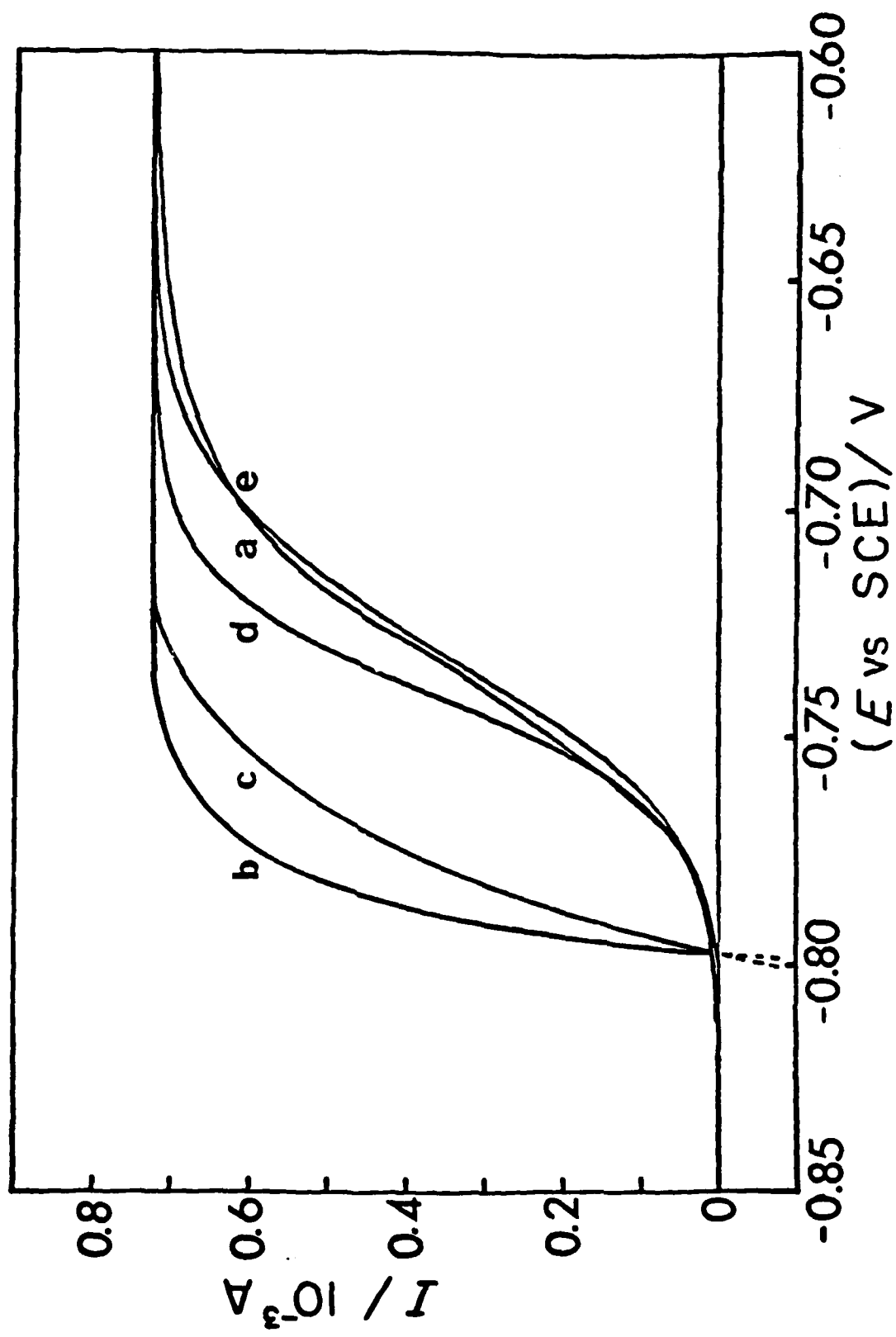


Figure 1

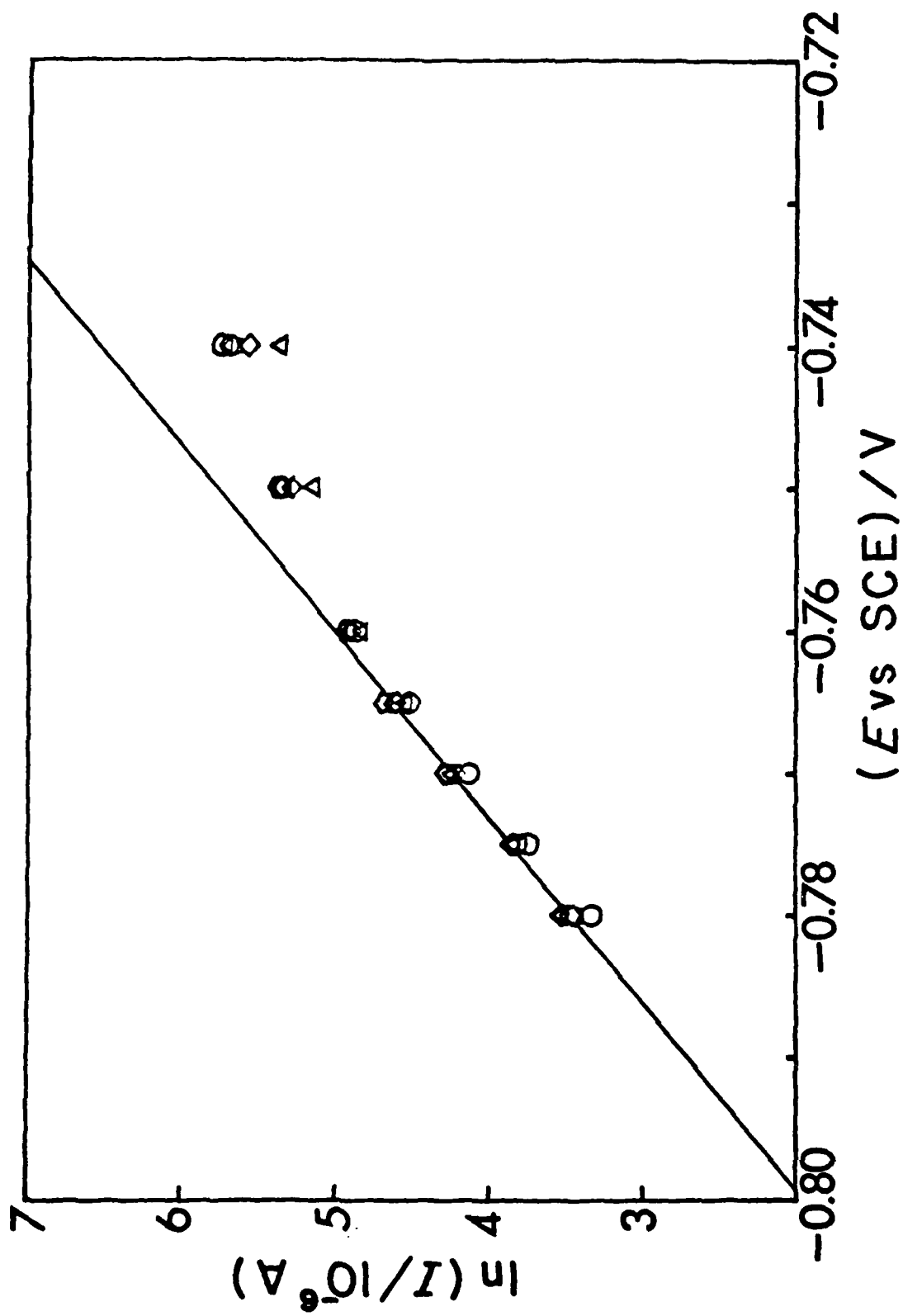


Figure 2

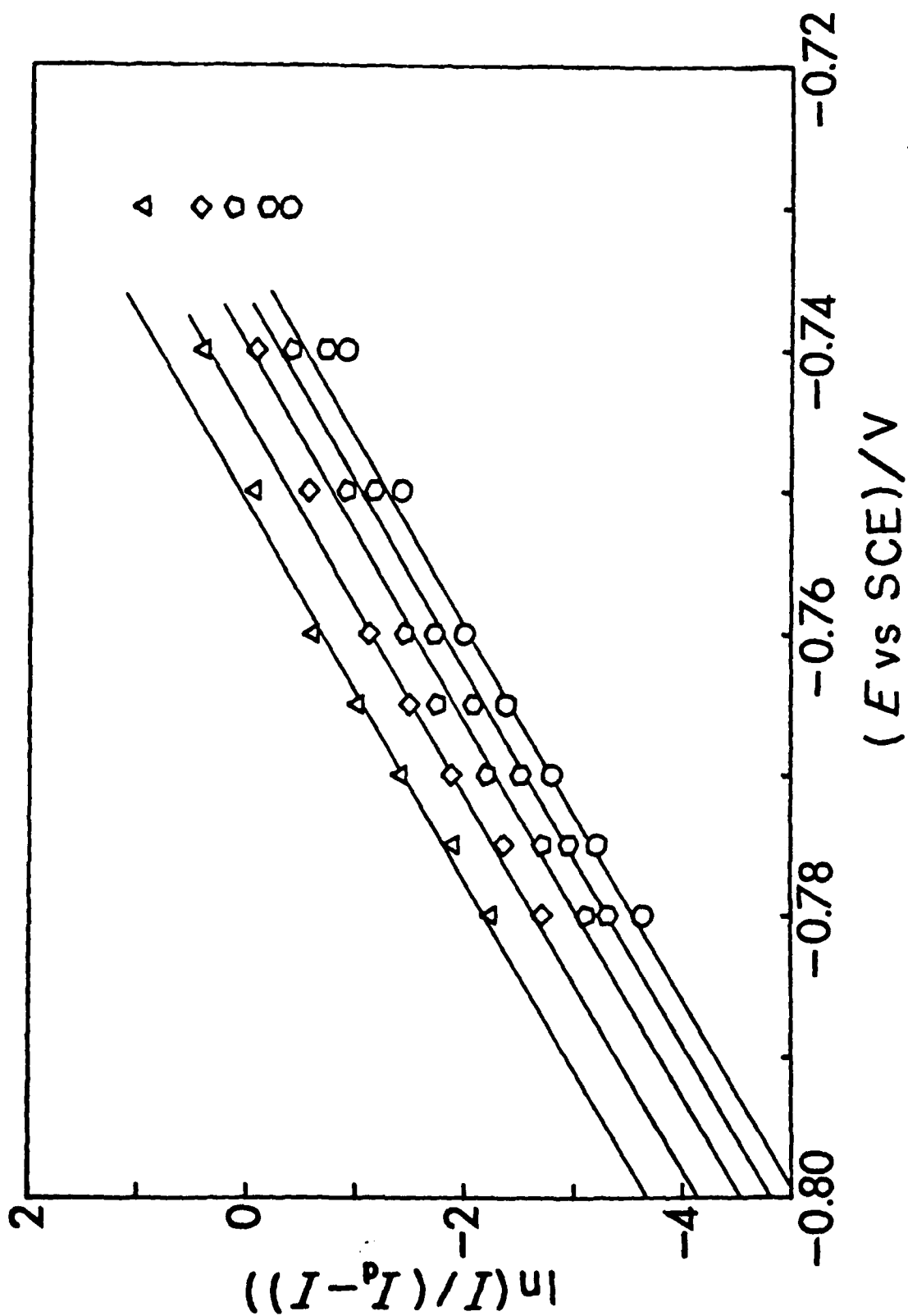


Figure 3

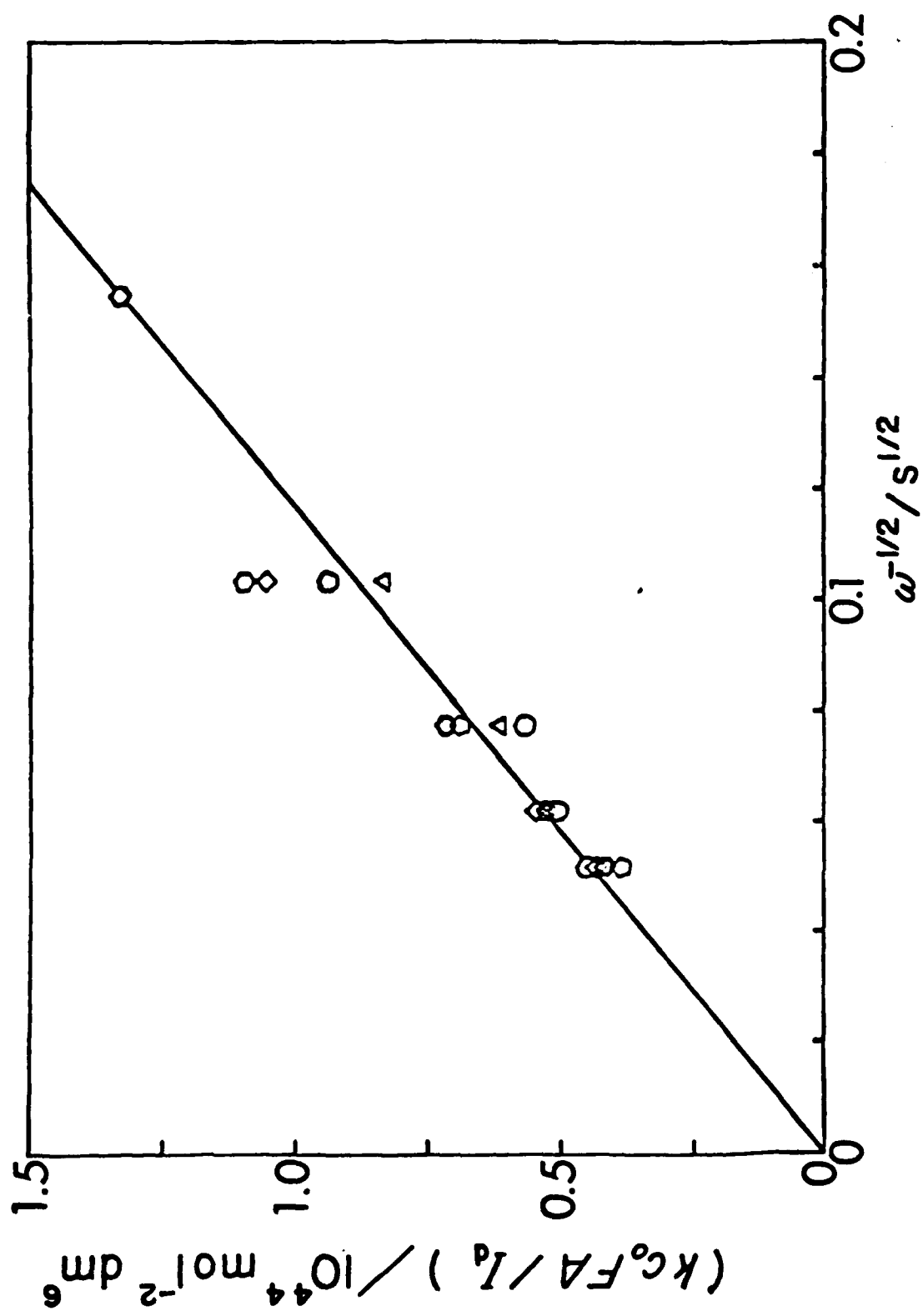


Figure 4

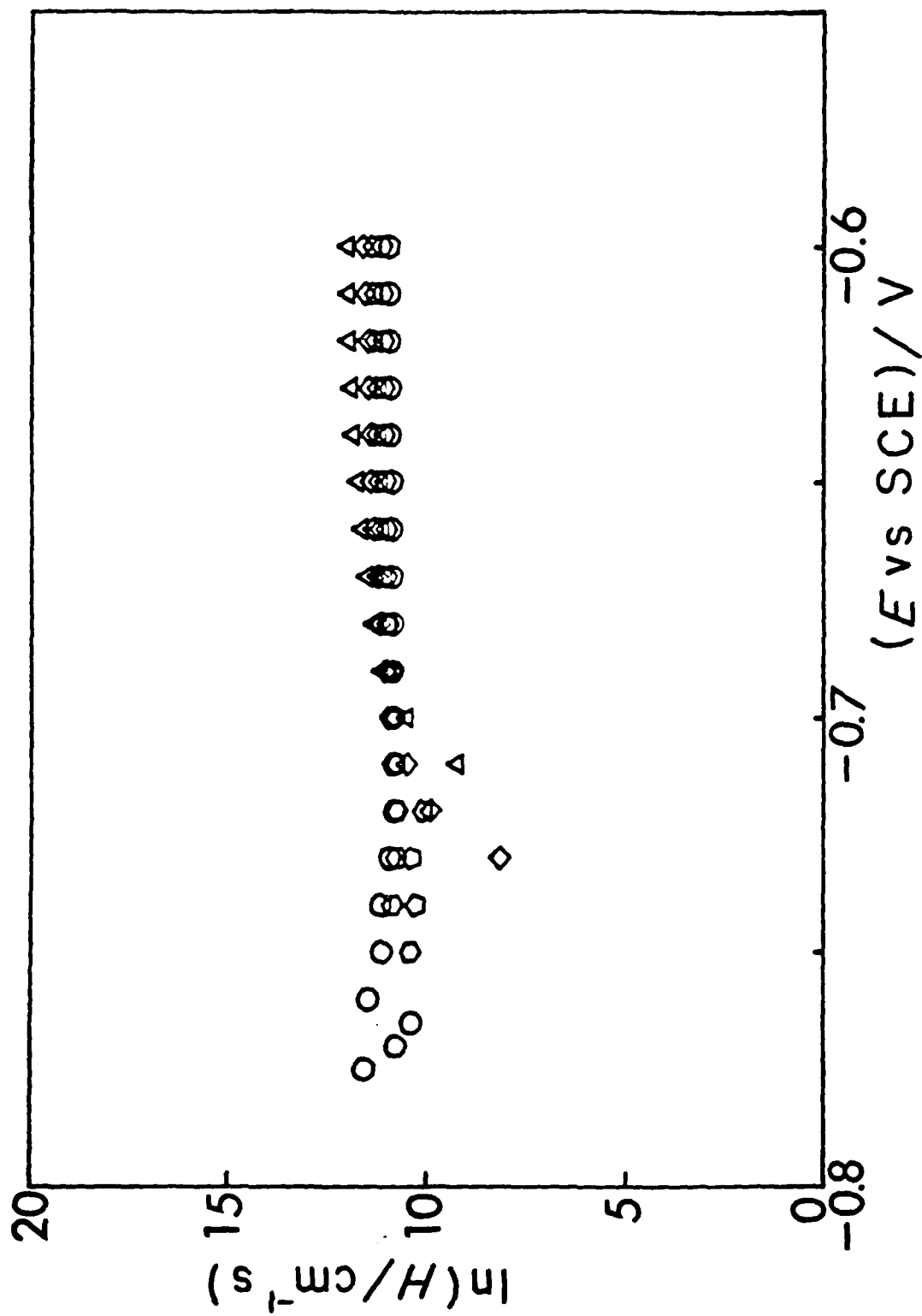


Figure 5

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